Sequential R&D strategy for synfuels

Martin L. Weitzman*

with the assistance of

Whitney Newey**

and

Michael Rabin***

The basic point of this article is that a "crash program" mentality leads to inappropriate questions and wrong answers about policy issues in large-scale government subsidized research, like the development of synfuels. R&D funding should be viewed as a sequential decision, not a once-and-for-all choice. Using some new results in the theory of information gathering, we apply an operational sequential methodology to analyze whether the U.S. government should subsidize the development of liquid synthetic fuels from coal.

1. Introduction

■ In economics as elsewhere, great confusion can result from posing issues of widely acknowledged significance in the wrong way. The wrong, but unfortunately common,[1] question to ask about large development projects like the government subsidization of synthetic fuels is: "Should we launch a crash program to build a large synfuel industry, say one or two million bbls./day by 1990?"

This all-or-nothing "Manhattan Project mentality" is the wrong way to pose the issue. It misses the point that substantial uncertainties about the net benefits of large-scale synfuel production (its process costs, environmental and social impacts, reactions to development of rural Western areas, cost of social infrastructure, etc.) make a sequential, information-yielding strategy the relevant policy.

The right question to ask is "Do synfuels look good enough now to make taking a further look worthwhile?" It is quite possible we might reject synfuels development when it is posed as a false all-or-nothing dilemma, yet be in favor of financing one more step to find out more information when the issue is correctly posed as a problem in sequential decisionmaking.

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* Massachusetts Institute of Technology.

** Massachusetts Institute of Technology.

*** Massachusetts Institute of Technology.

[1] Since the 1973 oil embargo, crash synfuel programs have been widely discussed in government documents. For example, see Interagency Task Force on Synthetic Fuels from Coal, Project Independence (1974), Synfuels Interagency Task Force (1975), U.S. 94th Congress (1977), U.S. 96th Congress (1979a, 1979b, and 1979c).

2. An example

■ A simple theoretical example may help to clarify many of the points we are making in this article.

Suppose a development process consists of two stages. The ultimate net reward R is a random variable which can only be collected if both stages are completed. We think of R as a sum of two independent random variables

$$R = R_1 + R_2,$$

where the random variable R_1 is revealed after stage 1 is completed and R_2 is revealed after stage 2 is completed.

For concreteness, suppose

$$R_1 = \begin{cases} \bar{R}_1 + \sigma_1 & \text{with probability } 1/2 \\ \bar{R}_1 - \sigma_1 & \text{with probability } 1/2 \end{cases}$$

$$R_2 = \begin{cases} \bar{R}_2 + \sigma_2 & \text{with probability } 1/2 \\ \bar{R}_2 - \sigma_2 & \text{with probability } 1/2, \end{cases}$$

where without much loss of generality, we assume

$$\sigma_1 > \sigma_2.$$

Thus, R is a random variable with mean $\bar{R}_1 + \bar{R}_2$ and variance $\sigma_1^2 + \sigma_2^2$. There are only two stages in this formulation, but note that with sufficiently many stages R would be approximately normally distributed. It costs K_1 in R&D costs to get through the first stage and K_2 to get through the second stage.

If we view the problem incorrectly as an all-or-nothing decision, the expected value criterion dictates that we should *not* proceed if

$$E[R] = \bar{R}_1 + \bar{R}_2 < K_1 + K_2. \tag{1}$$

When the problem is analyzed correctly as a sequential decision process, we may wish to proceed even though (1) holds.

Suppose an optimal policy is of the following form, as it is when (1) holds: *If* it is optimal to pay K_1 and proceed, then if R_1 turns out to be $\bar{R}_1 + \sigma_1$, we continue, whereas if R_1 turns out to be $\bar{R}_1 - \sigma_1$, we stop. Under such a policy, it is optimal to proceed now, provided

$$-K_1 + 1/2 \cdot 0 + 1/2(-K_2 + 1/2(\bar{R}_1 + \bar{R}_2 + \sigma_1 - \sigma_2) + 1/2(\bar{R}_1 + \bar{R}_2 + \sigma_1 + \sigma_2)) > 0,$$

which can be rewritten as

$$\bar{R}_1 + \bar{R}_2 + \sigma_1 > 2K_1 + K_2. \tag{2}$$

Thus, provided only that σ_1 is sufficiently large, it is optimal to proceed with sequential development even though the all-or-nothing decision based on (1) would be *not* to proceed. Note that with probability 1/2 we shall draw $\bar{R}_1 - \sigma_1$ after stage 1 and terminate the process. *Ex post* it may look as if R&D costs of K_1 were wasted under such circumstances, but that would be the wrong way of viewing the problem. It is exactly the possibility of termination before the end which encourages a sequential decisionmaker to go forward even though the standard cost-benefit criterion (1) looks discouraging.

The quantity σ_1 plays such a crucial role in the correct sequential continuation criterion (2) because it is a measure of how much information is obtained about the ultimate value of R after one stage of R&D. If sufficient information is obtained cheaply enough ($\sigma_1 - K_1$ is sufficiently large), we should proceed with another stage of development, even though we may not expect to see the project carried through all the way to completion.

Although the logic of this example is clear and the advantages of a sequential approach are often mentioned, the full implications of such an approach have not been sufficiently realized. In Roberts and Weitzman (1981), a theoretical model of sequential R&D is used to derive relatively simple investment criteria. In this article we would like to show that the investment criteria are sufficiently operational that they can be applied to evaluate whether liquid synthetic fuels from coal should be subsidized. The model is far from perfect and the data are elusive, but at least this sort of approach gives some means of addressing an important set of real R&D funding issues which have bedeviled researchers at DOE and elsewhere.

3. An economic argument for subsidizing synfuels

■ A wide variety of arguments have been put forward in favor of a government-subsidized synfuels program. To the economist, most of these arguments for market intervention seem questionable. The one argument we find truly convincing concerns nonappropriable learning externalities associated with reducing cost uncertainty. This "demonstration plant" effect seems to arise in a variety of contexts, with coal liquefaction being a prominent example of current interest.

An externality is involved since a private firm's investment decisions do not reflect full social costs and benefits. Consider a firm contemplating the building of a large-scale plant, which would reduce general uncertainty over coal liquefaction costs in the broad sense, including environmental costs. If the plant proves profitable, the firm receives the profits from that plant as well as others it may build. But the full social benefits include the profits from the entire resultant coal liquefaction industry, only a fraction of which can be captured by the original pioneering firm. Hence, the firm may choose not to invest when a full reckoning of expected benefits, should the project succeed, would dictate going ahead.

One can further distinguish between deterministic learning effects and those based on uncertainty over cost. By "deterministic learning effects" we mean riding down a known learning curve to build and operate the least-cost technology after going through a series of successively less expensive plants. There is a case for a subsidy here also, to the extent that the learning curve is defined over industry-wide aggregate cumulative output, and the firm cannot appropriate the lower costs to itself alone.

Both deterministic and stochastic learning effects offer potential cases for subsidies, and, formally speaking, both are incorporated in our model. However, we believe that for coal liquids, stochastic learning is the more important effect empirically. The wide variation in estimates of coal liquefaction costs, from \$24/bbl. to \$80/bbl., offers superficial evidence of cost uncertainty, while estimates of "learning curve" induced cost reductions for coal synthetics tend to be low.

4. The model

■ This section proposes a relatively simple model for determining whether coal liquefaction should be subsidized to learn about ultimate costs. After presenting the simple model, we suggest that a fuller and more complex approach would yield similar conclusions. A detailed, technical exposition of the model's central features is offered in Roberts and Weitzman (1981), which rigorously derives the optimal policy.

All the uncertainty over terminal costs and benefits of a potential coal liquefaction industry that can be eliminated by a subsidized development program is reflected in the ultimate cost/bbl. of coal liquids. Development of the project advances with subsidy outlays in a pay-as-you-go fashion, and the information revealed is translated into progressively less uncertain estimates of that ultimate cost/bbl. The stage of development of the process, including the learning that has taken place, is indexed by s, the amount of subsidy paid so far.

Let

C_s = ultimate cost/bbl. of coal liquids, given all information available when a subsidy of s has already been paid;
EC_s = expected value of C_s;
δ_s = standard deviation of C_s;
S = total subsidy required to push development project to completion;
P = world price of oil prevailing when potential coal liquefaction industry would come on line;
T = time lag until potential coal liquefaction industry comes on line, in years;
n = output of potential coal liquefaction industry, in bbls./day;
d = days/year coal liquefaction plant is producing output; and
r = annual real interest rate.

The variables S, P, T, n, d, and r are assumed to be given parametrically. All nominal variables are in 1980 dollars. The random variable C_s represents the ultimate cost/bbl. of coal liquids, conditional on information revealed so far by the development process, when subsidies totaling s have been paid. Costs are construed broadly as the average cost/bbl. in an industry of size n, taking account of any social, political, and environmental costs, such as deterioration of local air and water quality, destruction of wilderness, creation of boomtowns, etc.[2] Deterministic learning effects that would be enjoyed by the contemplated industry are also incorporated into C_s.[3]

If the project is pushed through to completion by subsidy payments totaling S, the mean cost/bbl. drifts stochastically from EC_0 to EC_S, while the standard deviation of the cost/bbl. is lowered deterministically from δ_0 to δ_S. As the project advances, the standard deviation of the ultimate cost/bbl., δ_s, falls, and the mean EC_S moves up or down.

We assume that the reduction in δ_s occurs linearly, as depicted in Figure 1.

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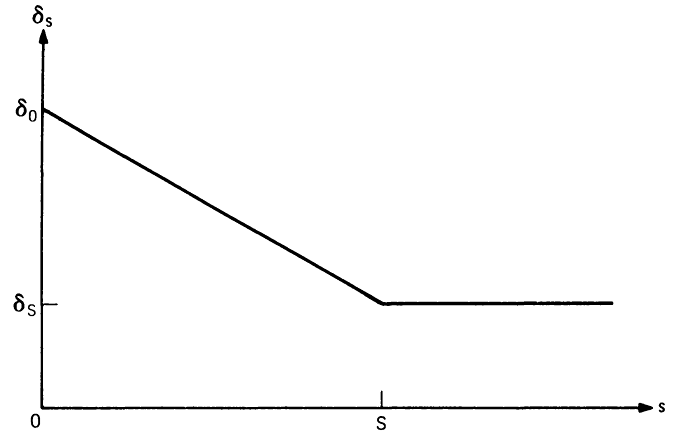
[2] Even without these broader costs, the "cost/bbl." of coal liquids is not a simple concept—capital costs must be attributed which requires use of the correct real interest rate in discounting and properly "seeing through" inflation. This is discussed in the next section.

[3] Deterministic learning effects produce an additive shift of the distribution of C_s. They would affect EC_s but not δ_s.

FIGURE 1

STANDARD DEVIATION AS A FUNCTION OF SUBSIDIES



This assumption permits considerable computational simplification,[4] and may be justified as a piecewise linear approximation to an arbitrary δ_s curve. With it, the subsidized project may be characterized by two numbers, δ_S and

$$\delta \equiv \delta_0 - \delta_S,$$

which is the total reduction in standard deviation obtained by pushing the project through to completion.[5]

Upon completion, an industry of fixed size n can be built. In a more general treatment n might itself vary depending on such factors as EC_s (the terminal expected cost/bbl.), but in this context n is treated as fixed. Assuming risk neutrality and an infinitely long-lived industry, the expected real net benefit of the industry as viewed from stage s, which we denote by B_s, is

$$B_s = \frac{1}{r} e^{-rT} nd(P - EC_s). \tag{3}$$

An optimal policy is sought to maximize the expected value of benefits minus subsidies. At each stage this optimal policy will indicate, on the basis of current information, whether to abandon the project or to continue its funding, and will take into account that an optimal funding policy is to be followed from that stage forward, by relying at each later decision stage on the information then available.

To present a sharp characterization of the optimal policy, we assume that C_s is normally distributed, i.e.,

$$C_s \sim N(EC_s, \delta_s^2). \tag{4}$$

Actually, the optimal policy is insensitive to the upper tail of the distribution of C_s because the development process should be terminated, yielding zero

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[4] In the general, nonlinear case, calculation of optimal policies requires numerical solution of partial differential equations.

[5] In our model, only the absolute reduction in δ_s affects the optimal policy, which does not at all depend on the level of irreducible uncertainty over costs, δ_S.

terminal benefits, when costs are revealed to be high. Consequently, the possibility that the actual cost/bbl. distributions may be highly skewed in the upper tail is not necessarily damaging to conclusions based on the normality assumption for the lower tail.

We assume that the accumulated subsidy payment, s, representing the project's stage of development, is a continuous variable. The project is assumed to be continuously reevaluated. Thus, for every s, a go or no-go decision is made about whether to continue subsidization. This assumption simplifies the mathematical characterization of the optimal policy.

Behind the scenes, we can think of C_s as a sum of a large number of independent random variables (much in the style of the example given earlier). Each stage costs some small amount (a dollar) to complete, and its completion causes one of the random variables to be realized, which shifts EC_s up or down as the value of the random variable is bigger or smaller than expected and simultaneously lowers the variance of the sum of the remaining random variables. In the limit, as the number of stages approaches infinity and each one is of infinitesimal size, we have a Wiener-like process with C_s normally distributed.

The assumptions of continuity, linear reduction in standard deviation, and normality imply that the system's state is completely summarized by the current mean of the ultimate cost/bbl., the total subsidy required to push the project to completion, and the total reduction in standard deviation of cost/bbl. afforded by completion. It is then sufficient to formulate an optimal decision rule for proceeding initially, based on the initial parameters S, δ, and EC_0, which latter parameter we shall henceforth denote without a subscript as EC. Once subsidies of s have been paid and the standard deviation reduced by $(\delta_o - \delta_S)s/S$, the remaining process is just like a complete one with changed initial parameters

$$S' = S - s, \qquad \delta' = \delta - (\delta_o - \delta_S)\frac{s}{S}, \qquad EC' = EC_s.$$

The optimal stopping rule can be stated as

$$\begin{aligned} &g(EC, \delta, S, P, n, d, T, r) > 0 \Rightarrow \text{continue} \\ &g(EC, \delta, S, P, n, d, T, r) < 0 \Rightarrow \text{terminate} \\ &g(EC, \delta, S, P, n, d, T, r) = 0 \Rightarrow \text{indifferent,} \end{aligned} \tag{5}$$

where, in general, the function $g(\cdot)$ depends on all the parameters. In this particular model, the function $g(\cdot)$ takes the explicit form

$$g(EC, \delta, S, P, n, d, T, r) = \delta\frac{\phi((P - EC)/\delta)}{1 - \Phi((P - EC)/\delta)} - \frac{re^{rT}}{nd}S, \tag{6}$$

where $\phi(\cdot)$ and $\Phi(\cdot)$ are, respectively, the standard normal density and cumulative distribution function.[6] For interpretive purposes it is convenient to take

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[6] See Roberts and Weitzman (1981, formula (6)). In the notation of that article we set,

$$\mu = \frac{1}{r}e^{-rT}nd(P - EC)$$

$$\sigma = \frac{1}{r}e^{-rT}nd\delta$$

$$C = S.$$

advantage of the fact that P and EC enter the right-hand side of (6) only through their difference, $(P - EC)$, and to regard (5) and (6) as implicitly defining a cutoff value of $(EC - P)$ as the value of a function $f(\delta, S, n, d, T, r)$.

The optimal stopping rule can then be reexpressed as:

$$\Delta \begin{matrix} < \\ > \\ = \end{matrix} \Delta^* \begin{matrix} \Rightarrow \text{continue} \\ \Rightarrow \text{terminate} \\ \Rightarrow \text{indifferent,} \end{matrix} \tag{7a}$$

where

$$\Delta = EC - P \tag{7b}$$

and

$$\Delta^* = f(\delta, S, n, d, T, r). \tag{7c}$$

Δ is the estimated coal liquefaction cost premium over imported oil. Given δ, S, and the other parameters, there is a cutoff cost premium Δ^*. If the current estimate of the cost premium exceeds the cutoff value, it is optimal to abandon the project. If Δ is below the cutoff value, the optimal policy is to continue.

There is, unfortunately, no simple or heuristic story for formula (6). Multistage sequential decisionmaking problems are intrinsically very complicated, and this has probably hindered their application. In some sense, we are lucky to have a formula as elementary as (6), given the intrinsic complexity of the underlying problem.

Properties of the function $f(\cdot)$ and, hence, of the optimal cutoff cost premium, can be inferred from (6) together with the identity,

$$g(\Delta^*, \delta, S, P, n, d, T, r) \equiv 0. \tag{8}$$

The following basic results can be readily derived, assuming $n, d, T, r > 0$:

(i) $\delta \to 0$ implies that $\Delta^* \to -\dfrac{re^{rT}}{nd}S$;

(ii) $\delta > 0$ implies that $\Delta^* > -\dfrac{re^{rT}}{nd}S$;

(iii) $\delta \to \infty$ implies that $\Delta^* \to \infty$;

(iv) $S \to 0$ or $e^{-rT}\dfrac{1}{r}nd \to \infty$ implies that $\Delta^* \to \infty$;

(v) $S \to \infty$ or $e^{-rT}\dfrac{1}{r}nd \to 0$ implies that $\Delta^* \to -\infty$.

Condition (i) expresses the fact that if there is no reduction in uncertainty, the subsidy program is evaluated by the standard expected present value criteria, i.e., proceed if

$$V = \frac{1}{r}e^{-rT}nd(P - EC) - S > 0. \tag{9}$$

This is also the relevant calculation if the decision to proceed with funding the project, once made, is irrevocable. However, as condition (ii) shows, a project can fail by the traditional criterion but still be worth pursuing in a sequential policy. This difference can be quite significant, as (iii) indicates. The bias toward tentatively going ahead with a project is more pronounced as the variance of benefits is greater, because the realization of a stage removes more uncertainty and allows a better informed decision to be made. The next section reveals that our best estimates for coal liquefaction imply $\Delta^* > 0$, so that the cutoff value of expected terminal benefits is negative without even taking account of subsidy payments. Less than zero benefits would, of course, never be realized because the process would be discontinued before completion.

Performing comparative statics on (6) and (8), one finds that as δ increases with other variables remaining constant, Δ^* increases. With greater uncertainty about the ultimate cost/bbl., a higher cost premium is tolerable since it is more likely that the next few stages will reveal unexpectedly low costs. Also, *ceteris paribus*, as S increases, Δ^* falls. The rationale for this is obvious.

Inspection of (6) also reveals that the optimal cutoff, Δ^*, depends on its arguments in a much more specific fashion than (7c) suggests. For example, S, n, d, T, and r enter only through the term $(re^{rT}/nd)S$. Hence, for example, proportional changes in n are completely offset by equal proportional changes in S. We use this fact to simplify sensitivity analysis. Also, fixing the other parameters, Δ^* is homogeneous of degree one in δ and S. Since δ_s is linear in S, this implies that if the other parameters remain unchanged as subsidies are paid, Δ^* declines linearly to zero.

Now we make a series of remarks on the model and its applications.

First, the continuous sequential process is best thought of as a mathematical idealization which approximates situations with large but finite numbers of intermediate potential stopping points. In fact, we suspect that, as with compound interest, the number of stopping points need not be large before the approximation is very good, and that 3 or 4 is just like infinity, for practical purposes. Our calculations show that the approximation is not terrible even for just one stopping point.[7] And there are surely a fair number of stopping points.

Second, the model makes no selection of *which* subsidy program to choose. We assume that the correct sequencing of stages, with R&D, pilot plants, commercial-sized plants, etc. has already been made on other grounds. We also assume that the mechanics of the funding package are chosen efficiently; for example, if private firms are subsidized, then output subsidies are preferred to input subsidies, etc. (Schmalensee, 1980, pp. 14–15). And, we draw no formal distinction between alternative coal liquefaction technologies.

Third, the basic simplifying assumption of linear reduction in δ_s is not really essential to the theory. The general case is discussed in Roberts and Weitzman (1981). The form of the optimal stopping rule will still be given by (7), but (6) will no longer give the correct $g(\cdot)$ function. Various simplifying features, like the first degree homogeneity of Δ^*, given n, d, r, and T, disappear in the general case. When the δ_s curve is convex, like the dotted line in Figure 2, Δ^* will tend to be initially higher than in the linear case, since the next few stages purchase a steeper reduction in δ_s. The reverse holds when δ_s is concave, like the solid line in Figure 2. In any case, little enough is known about the

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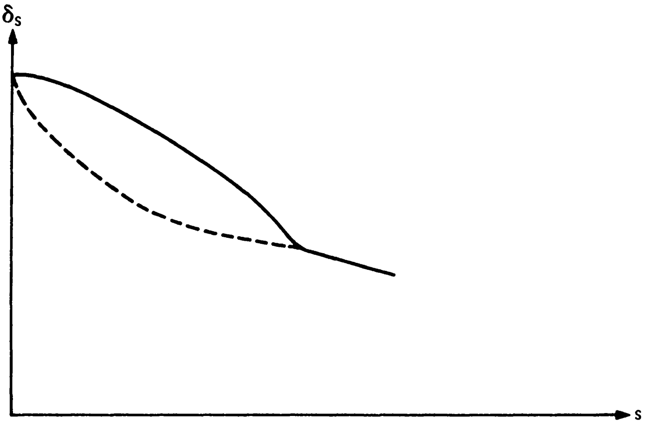
[7] In the case mentioned with one potential stop after completing the subsidy program, the $g(\cdot)$ function would be

$$g(EC, \delta, S, P, n, d, T, r) = \Phi\left(\frac{P - EC}{\delta}\right) + \delta\phi\left(\frac{P - EC}{\delta}\right) - \frac{re^{rT}}{nd} S.$$

FIGURE 2

STANDARD DEVIATION AS A FUNCTION OF SUBSIDIES IN THE GENERAL CASE



likely shape of δ_s to justify a major departure from our seemingly neutral piecewise linear approximation.

Fourth, the parameter T, representing the time delay until the potential industry could come on line, is best thought of as an average or summary approximation of continuous developments. In a more general model, the industry would be constructed over a period stretching from before the T year delay to after it. Our model is essentially timeless in the sense that consideration of optimal timing and speed of development are suppressed.

Finally, we note that the procedure generating current estimates of ultimate cost EC is assumed to be subject to a basic consistency condition. EC is supposed to be a true expected value, so that it should not tend to move *systematically* up or down as new information is revealed. Any tendencies for the mean estimate to rise or fall because of the changing quality or sophistication of the estimating process are assumed to be immediately taken into account.[8]

Although the model of this article is admittedly simplistic, it captures the main features of the sequential funding decision. The next section analyzes the simple model's implications for optimal coal liquefaction policy by using our estimates of the relevant parameters.

5. Applying the model

■ The data we have used are those available in mid-1980. Hereafter these data will be referred to as current.

For our base case, we have used the following parameter values:

T = 10 years;
n = one million bbl./day;
r = 5%;
S = \$10 billion;
d = 325 days/year; and
δ = \$10.

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[8] Such tendencies have been noted, e.g., in Merrow *et al.* (1979).

The value of the optimal cutoff cost premium, Δ^*, implied by these parameter values and equation (7) is \$11.00.

One million barrels per day is our first estimate of the production capacity of the mature industry should coal synthetics turn out to be profitable. In a more general model, industry size would depend on the profitability of coal synthetics. A million barrels a day may seem small, even if the processes only become marginally profitable. We believe with others, however, that in a more general model the optimal use of resources would involve much direct use of coal, low and medium-Btu coal gasification, and upgrading of petroleum distillates, rather than use of coal synthetics to fill current demand for high-grade liquids.[9]

The 5% discount rate we have chosen is lower than the discount rates used by many energy researchers to evaluate energy projects.[10] But, as we argue below, the correct discount rate in this context is the real rate of interest, which is almost certainly not greater than 5%.

Reasonable values of S and δ could not be read directly from the relevant literature, since, until now, the concepts to justify their calculation have been lacking. Rather, we had to infer plausible values from statements we could find and bring to bear. The following considerations entered our estimate of S. From the published literature and from personal communications with energy specialists, we estimate that the construction and operation of a full-sized (50,000 bbl./day) plant will eliminate most of the reducible uncertainty about a particular process.[11] Tentative calculations suggest that the present value of subsidies required for one 50,000 bbl./day plant is \$2–3 billion.[12] Thus, \$10 billion would provide for construction and operation of three to five full-sized plants, each using a different process, and also possibly provide for other types of research in coal synthetics. The construction of three to five coal synthetics plants has been implicit in discussions of a synfuels "information" program

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[9] White, Director of the MIT Energy Lab, indicated that "we as a nation should not . . . consider synfuels as a petroleum replacement that has the same economics as petroleum . . ." (1980). Stokes reported: "The future of liquid synthetic fuels produced from coal . . . is far from clear. And long before gasoline will be made from . . . [coal or shale oil], it will be made from the petroleum residuals which are now burned as industrial fuel, with coal in one form or another replacing those petroleum residuals as basic fuel" (1979, p. 32).

[10] Examples are found in Ericsson and Morgan (1978) and Synfuels Interagency Task Force (1975). The former uses a 10% discount rate and the latter, a 15% rate. Also, it is well known that discount rates used in evaluating power projects are much higher than 5%.

[11] The energy specialists referred to include Dr. John Deutch of MIT and DOE, James Harlan of Harvard, and Dr. J. Longwell of MIT.

[12] Given a current cost/bbl. of coal liquids of \$44 and a current price of oil of \$30, let the price of oil rise at 2% per year

$$p(t) = 30e^{.02t},$$

and let the future cost/bbl., $C(t)$, be given by

$$C(t) = 22 + 22e^{.02t}$$

(i.e., half of the cost/bbl. rises at the same rate as oil prices). Then for a 50,000 bbl./day plant operating 330 days/year over an infinite life, the present value of the subsidy (with a discount rate of 5%) is

$$-330 \times 50{,}000 \times \int_0^\infty ([30 - 22]e^{.02t} - 22)\bar{e}^{.05t}dt = \$2.9 \text{ billion.}$$

involving the construction of 200,000 to 400,000 bbl./day of synfuels capacity.[13] The construction of several coal synthetics plants in several places in the United States would provide information about environmental effects, public reaction, and infrastructure costs.

The $10 figure for δ is the standard deviation in cost/bbl. which is eliminated by spending $10 billion. This standard deviation includes uncertainty about capital costs, operating and maintenance costs, plant throughput, environmental related costs, infrastructure costs, etc. Published remarks suggest that a $10 standard deviation does not overestimate the downside uncertainties in ultimate coal synthetics cost which we have described. In Congressional hearings (1979, p. 619), Brown and Kahn suggested that the cost per barrel is unlikely to decline through "technical improvements" to less than one-third the expected cost.[14] Merrow *et al.* (1979) analyze data for first-of-a-kind energy projects and find the inflation-adjusted ratio of last available cost estimate to first available cost estimate to have a variance of ½.[15] Also, private communications with energy specialists have led us to believe that the $10 standard deviation is about right.[16]

The Δ^* value (to the nearest dollar) implied by our base case parameter values is $11. This means that if our current expectation of $EC - P$ is less than or equal to $11.00, development should proceed although it might well be optimal to stop it later. If $EC - P$ is greater than $11.00, none of the $10 billion should be spent. Recall that EC is the current estimate of ultimate cost/bbl. and P is the world price of oil in 1990, both in real terms (1980 dollars).

To decide whether to proceed with coal synthetics development, we require a current EC. However, the cost/bbl. is not a completely simple or one-dimensional concept. A typical flaw in calculating cost/bbl. is that a nominal instead of a real interest rate is used, thereby making capital costs appear too large.[17] The high nominal rates reflect inflation, and they can be used consistently only if rising variable input and output prices are also taken into account.

The appropriate concept is the constant hypothetical *real* price of a barrel

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[13] In Synfuels Interagency Task Force (1975) the information program involves 350,000 bbls./day capacity, and the Congressional Budget Office report to the U.S. 96th Congress (1979c) states: "A certain production threshold is necessary to develop the technical, environmental, and economic information needed to choose the most efficient technologies and resources that should be developed over the long run. Although this threshold is difficult to estimate, it probably falls between 200,000 and 400,000 barrels of oil equivalent per day. This represents four to eight large scale plants using different alternative technologies and resources."

[14] The full text was: ". . . [L]arge future reductions from currently projected capital investments are considered to be relatively unlikely. Consequently if the estimated $15 per barrel pricing—with restructured financing—were valid for the emerging synfuel technologies (such as Gulf's SRD, Ashland's H-Coal, or Exxon's EDS processes) or perhaps for the existing ones (Fischer-Tropsch liquids, Lurgi Gasification, methanol)—then it is unlikely to decline to $10 per barrel through technical improvements during the next decade or so. The point is that sufficiently large cost reductions or gains in efficiency to delay investments in existing processes are not expected from the newer technologies."

[15] Merrow *et al.* (1979, p. 87) document cost increases in first-of-a-kind projects over several subintervals of project development. Unfortunately the projects examined bear less directly on the cost increases over the later stages of development, which would be more appropriate for making inferences about future synfuel cost changes.

[16] Dr. John Deutch of MIT and DOE, James Harlan of Harvard, Dr. Longwell of MIT, Dr. David C. White and Dr. Malcolm A. Weiss of the MIT Energy Lab were all helpful in this regard.

[17] Rates of 15% and 28% are used by Weiss *et al.* (1979).

of coal synthetics which would yield a zero present discounted profit. Let

VC = marginal variable cost/bbl. of coal synthetics;
F = fixed cost of coal synthetics plant of capacity k;
r = real discount rate; and
$\bar{C}$ = real cost/bbl.

Then $\bar{C}$ should satisfy

$$0 = -F + \int_0^{\infty} (\bar{C} - VC)kde^{-rt}dt = -F + \frac{(\bar{C} - VC)kd}{r}$$

or

$$\bar{C} = \frac{rF}{kd} + VC.$$

In reality VC, k, and d in each time period are uncertain and will have distributions with means that change over time as a result of learning effects. In a more elaborate analysis, $\bar{C}$ might include terms reflecting the existence of taxes. The addition of these complications will affect $\bar{C}$ in various ways we have not attempted to quantify.

To simplify we shall use

$$EC = \frac{r\hat{F}}{kd} + \widehat{VC} + Adj$$

to estimate EC, where $\hat{F}$ and $\widehat{VC}$ are current industry estimates, r, and d have the values specified earlier, k is 50,000 bbl./day, and Adj is an adjustment for "cost overruns," which is net of learning effects, so that EC will include any learning effects that occur during development.

We have specified the fixed cost of a coal synthetics plant (F) as \$3 billion. The capital cost estimates which were available to us appear in the Appendix. They are all in mid-1979 dollars. When updated to 1980 dollars by adding 10%, only the Fluor Corporation estimate is (slightly) greater than \$3 billion. The other (1980 dollar) estimates are well under \$3 billion. The Fluor estimate was for a South African Fischer-Tropsh plant, modified for the United States, and was made by using available data on the South African operation. It seemed the most reliable estimate, and hence we gave it the greatest weight.

We have set VC at \$25 per barrel, and we discuss this estimate in detail in the Appendix. It is based on February, 1980, coal prices and Stanford Research Institute estimates of synfuel operating and maintenance costs as a percentage of capital costs.[18]

With $\widehat{VC}$ = \$25 and $\hat{F}$ = \$3 billion, $\bar{C}$ is \$34/bbl. Since we believe that the underlying cost estimates on which $\bar{C}$ is based reflect "best case" projections rather than true expected values, we have used Adj = \$10 (one standard deviation) as a cost overrun adjustment.[19] This yields \$44 as our base case estimate of EC.

The use of this kind of adjustment is not unprecedented. In a report prepared for the Senate Subcommittee on Synthetic Fuels (1979, p. 179) Cameron

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[18] We have not tried to distinguish fixed and variable cost components of operating and maintenance costs, since this distinction does not affect our calculation.

[19] As an example of cost overrun, $\hat{F}$ = \$4.5 billion, d = 300 days, and VC = \$30 per barrel, gives $\bar{C}$ of \$44 per barrel.

Engineers states: "Engineering estimators realize they cannot foresee all costs. They try to account for this by adding a contingency allowance, based on past experience or simply intuition. Most estimates use a contingency allowance on the order of 15 percent. The contingency allowance should be related to the state of knowledge about a process. The proper contingency allowance for direct coal liquefaction is arguably appreciably higher, perhaps approaching 50 percent." Our contingency allowance is 29%, which is reasonable, since our estimate involves less uncertain indirect coal liquefaction costs.

At this point in our analysis there is a dilemma concerning how to proceed further. Our current estimate of the expected cost/bbl. of synfuel is $44, and we take $30 as the current (1980) price of oil. There are two basically different approaches for determining the future relation of coal synthetics cost to price. One popular approach is to hold the cost constant at $44 per barrel and project some price of oil in 1990. With ten years of exponential growth of some plausible real oil price growth rates (e.g., 4%) this approach completely eliminates the need for our research and development analysis; coal synthetics are profitable in the year 1990. We think this is an extreme approach. The past history of synfuel cost estimates has featured estimates "just above" the price of oil for over 25 years. Synfuel cost estimates have even jumped discontinuously when oil prices have. Since the 1950s, the connection between projected synfuel costs and oil prices seems to be the most stable empirical relation in energy economics. This last observation leads to the second extreme approach, which is to take the current margin between cost and price as the best estimate of the cost-price margin in 10 years' time.

The correct approach probably lies somewhere between these extremes. The real cost of coal synthetics is undoubtedly related to the real price of oil (for example, through the price of coal). But the process that has generated increases in the estimated real cost of coal synthetics is not well understood.

The current Δ is $\$44 - 30 = \$14$, which is $3 larger than Δ^*. Therefore, using the second extreme approach, with the current Δ as an estimate for Δ in 1990, we should not proceed with coal synthetics development. However, for proceeding to be optimal, it is only required that Δ for 1990 to be $3 less (in 1980 dollars) than the current Δ. As an example, if feedstock costs (set equal to $12 of the $44 cost/bbl. estimate) grow at the same rate as the price of oil, and all other costs are unrelated to oil prices, any rate of increase of real oil prices greater than 1.5% makes proceeding now optimal.[20] If half of the $44 cost per barrel grows at the same rate as the price of oil, while half remains constant, then at any rate of increase of the price of oil above 3.2%, the optimal choice is to proceed now with development. We conclude that under a range of circumstances which are plausible it is optimal to proceed now with a coal synthetics development program. Note, however, that this conclusion depends on the path

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[20] Our estimates for $EC - P$ in 1990 are formed by assuming $P\ (1990) = P\ (1980)\ e^{g10}$, with g defined as the annual growth rate of the real oil price, and by assuming $\bar{C}\ (1980) = C_0 + C_1$ and $\bar{C}\ (1990) = C_0 e^{g10} + C_1$. These assumptions result in

$$\Delta = EC - P = (C_0 - P\ (1980))e^{g10} + C_1$$

for 1990. Δ is decreasing in g as long as $P\ (1980) > C_0$. Setting $C_0 = \$12$ feedstock costs, $P\ (1980) = \$30$, $C_1 = \bar{C}\ (1980) - C_0 = \$44 - \$12 = \$32$, and solving $\Delta = (-18)e^{g10} + 32 = \Delta^* = 11$ for g give $g = 1.5\%$.

TABLE 1

PARAMETRIC ANALYSIS OF Δ^*

S	δ		
	$7.50	$10.00	$12.50
$ 5 BILLION	$10	$16	$21
$10 BILLION	$7	$11	$16
$15 BILLION	$4	$ 8	$12

of the real oil price. In particular, if it is expected that the real oil price will not rise at all during the next 10 years, it would not be optimal to fund coal synthetics.

Table 1 shows the effect on Δ^* of altering some of the parameter values. We use alternative values of S and δ and compute the associated Δ^*. Note that in Table 1 a decrease in the subsidy, S, raises Δ^*. Increases in δ, implying a greater probability that coal synthetics become profitable, also raise Δ^*. The total subsidy S affects Δ^* only through S/n, so that halving S has exactly the same effect as doubling n, and *vice versa*. It is apparent that percentage changes in δ affect Δ^* more than percentage changes in S. The long shot change that coal synthetics might turn out to be profitable is really the entire reason for proceeding with development now. It is the lower-tail cost uncertainty that drives this model. If it were known now that coal synthetics would never be profitable, then not another penny should be spent for their development. Five of the nine Δ^* values shown in Table 1 are greater than or equal to $11. If our estimates of Δ in 1990 were taken to be $10, two-thirds of the Δ^* values yield a decision to proceed. The decision to proceed seems fairly robust to changes in the parameter values.[21]

6. Conclusion

■ The model we have presented takes into account the essential sequential nature of research and development. The "value of information" is captured by a formula that is relatively simple when one considers the inherent complexity of the sequential problem. An uncertain final outcome to a research and development program makes development much more attractive than it is with the usual expected net benefit calculation. The sequential nature of the research and development process allows the possibility of proceeding on the chance that results *might* turn out to be very good. This approach to the research and development problem involves many simplifications, including the possibility of continuous review. It is our impression, however, that a reasonable process with a moderate number of steps would give stopping values which are close to those of the model, and we believe that the ease of computation outweighs the slight inaccuracy. This approach can be applied to assess the economic benefits of research and development programs in general. To date, such a sequential calculation has either been considered difficult or not considered at all.

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[21] Δ^* values were computed for a one-step development process for the parameter values used in Table 1. Each of the one-step Δ^* values was less than one-half the corresponding continuous development Δ^* value. All but two remained positive. Also the one-step Δ^* is less sensitive to changes in δ.

Applying this methodology to coal synthetics development, with parameter values that appear to fit the facts and realistic oil price growth rates, we have determined that it is optimal to proceed with a coal synthetics development program. But coal synthetics should be pursued with careful attention to the results of current research and development. If results raise our expectation of coal synthetics profitability, development should continue; however, if a "disaster" occurs, or even if our expectations remain the same for some time, then coal synthetics development should be dropped. The original decision to proceed is entirely a result of the possibility that coal synthetics might be profitable at the end of the development program. If this possibility is not confirmed though research and development, coal synthetics development should be shelved, at least until conditions appear more favorable. In fact, using our base case parameter values, we find that the probability that coal liquefaction ultimately proves desirable is only $1/6$. This is a very different way of looking at the problem from the "crash program" mentality.

The conclusion to proceed holds under some changes in parameter values, and the particular changes considered indicate that the optimality of starting development is fairly robust. Though the development program envisioned in this article is not like the current policy, we think that it is actually more reasonable. The government could improve its synfuels program by explicitly recognizing the essential sequential nature of coal synthetics development and organizing a research strategy around this crucial feature, instead of almost ignoring it.

Appendix

■ We acknowledge the help of James Harlan of Harvard in obtaining these estimates.

☐ **Capital costs.** We have plant capital cost estimates from several sources. These estimates are listed below. The estimates shown are in mid-1979 dollars:

source	capacity	est. plant cost
Fluor Corp. (1979)	65,000 bbls./day	\$3.6 billion
U.S. DOE (1979)	50,000 bbls./day	\$2.5 billion
Cameron Engineers (1979)	50,000 bbls./day	\$1.6–2.0 billion.

We use \$3 billion 1980 dollars as our point estimate of the capital costs of a 50,000 bbls./day plant.

☐ **Operating and maintenance costs.** Our operating and maintenance cost estimate sources are the Braun Corp. and the Stanford Research Institute. For comparability purposes these estimates are in the form of the ratio of annual operating and maintenance costs of plant facilities investment. Braun Corp. in ERD/AGA (1976) sets this ratio at .079. SRI (1978) gives an estimate of .118, but a more recent range of estimates, from .07–.10 was reported by SRI at First Annual Client Conference for SRI, International Synthetic Fuels Program, in March 1979. We have chosen .08 for use in our cost estimates. This gives operating and maintenance cost/bbl. of

$$\frac{.08 \times \$3 \text{ billion}}{50{,}000 \times (365 \times .9)} = \$15/\text{bbl.}$$

☐ **Feedstock costs.** The coal price figure we have used is $1.00 per million Btu. February, 1980, prices for delivered coal, reported in *Monthly Energy* Review (1980), range from $.75 per million Btu near Western coal fields to $1.25–$1.50 per million Btu near the Ohio Valley. We have also used figures of .60 for conversion efficiency, which was given to us by James Harlan, and 5.8 million Btu per barrel of product, which is in common use and was taken from several sources including James Harlan. These numbers yield

$$\text{feedstock costs} = \frac{\$1.00 \times 5.8}{.60} = \$10 \text{ per barrel.}$$

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